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TECHNICAL REPORT: NAVTRAEQUIPCEN IH-322

GLIDESLOPE DESCENT-RATE CUING TO AID CARRIER LANDINGS

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Two techniques for providing descent rate information to pilots making carrier landings were evaluated and shown to be effective in a flight simulator. Landing performance of experienced Naval aviators was tested in the Visual Technology Research Simulator, with a conventional Fresnel Lens Optical Landing System (FLOLS) and with a simple modification to the FLOLS to include variable-length vertical light arrays, or arrows.

The FLOLS, which is used for glideslope guidance during carrier approaches, provides zero-order or displacement information for the pilot to judge whether →

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20. ABSTRACT

he is above or below the glideslope. Aircraft system dynamics can create substantial lags between an incorrect control input and the resulting error indication from the FLOLS. The techniques that were evaluated compensated for that lag by providing first-order or rate information to the pilot.

The two techniques involved different first-order drive algorithms. One system, designated the RATE display, showed the difference between the aircraft's actual descent rate and the descent rate that would maintain its present glideslope angle with respect to the FLOLS. The other, designated the COMMAND display, showed the magnitude of descent rate correction needed, and indicated a no-error condition when the pilot was tracking the glideslope or returning to it at an appropriate rate of closure.

The first-order displays improved glideslope tracking performance significantly throughout the approach. Lineup performance was not adversely affected. Differences between the two first-order configurations favored the COMMAND display. The pilot subjects and Landing Signal Officers involved in the evaluation were unanimous in strongly endorsing the modified systems and indicated a preference for the COMMAND over the RATE display.

Currently available equipment could be used to modify the existing FLOLS on aircraft carriers at a relatively low cost. If comparable improvements in glideslope performance as found in the simulator are found in carrier operations, boarding rates and glideslope-related accident rates can be expected to improve substantially.

PREFACE

The authors would like to acknowledge the encouragement and support of several people who were important to the success of the research described in this report.

The assistance of Mr. J. Bolwerk, Naval Air Force, U.S. Pacific Fleet (Code 316B), and Mr. S. R. Johnson, Naval Air Engineering Center, NAS North Island, is gratefully noted for providing early encouragement and guidance to the senior author.

CDR Charles Sammons, Chief of Naval Operations (OP-593B) and CDR Charles Hutchins, Naval Air Systems Command (AIR-340F) were quick to realize the potential value of a descent rate cuing system in the fleet. CDR Sammons provided strong support for a simulator evaluation of the proposed concept and CDR Hutchins tasked the Naval Training Equipment Center to conduct the research under the Visual Technology Research Simulator (VTRS) project.

The technical support provided by the following individuals associated with the VTRS program is acknowledged with gratitude: from the Naval Training Equipment Center (Code N-732), Walter S. Chambers, Patricia Daoust and Edward Holler; performing under Contract N61339-78-C-0060, Helene Iavecchia, Daniel Sheppard and Daniel Westra of Canyon Research Group, Inc. and Clark Getz of Appli-Mation Inc.; performing under Contract N61339-78-C-0156, Jack Davis and Karen Thomley, students at the University of Central Florida.

During the first week of the experiment two Landing Signal Officers were present during testing, grading each approach as well as taking part in the written evaluations. They were LCDR Jerry Singleton, Officer-in-Charge, LSO School, NAS Cecil Field, FL, and CAPT Craig Johnson, USMC, also from the LSO School. Their support has been invaluable.

Acting as liaisons between COMLATWING ONE, NAS Cecil Field and the Naval Training Equipment Center were CDR Kenneth Cech and LCDR Robert Elliott. They were very helpful in arranging for the participation of Fleet pilots in the experiment.

Finally, we would like to thank the following pilots stationed at NAS Cecil Field, who served as subjects in the experiment. From Light Attack Wing One: CDR J. J. Coonan, LT M. Fitzgerald, LT B. Ritzert, LTJG J. Cantu, LTJG W. Patrick, and LTJG P. Anderson; from Air Antisubmarine Wing One: LT M. Ness, and LT D. Sammons.

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SECTION I

INTRODUCTION

PROBLEM

The Fresnel Lens Optical Landing System (FLOLS) provides primary glide-slope displacement information for a carrier approach to landing. It consists of light sources behind five vertically stacked Fresnel lenses that are situated between two horizontal light arrays known as the datum bars. The array of lenses and lamps provides a virtual image which appears to the pilot as a single light located 150 ft. behind the datum bars. This light is known as the meatball. The meatball is visible to the pilot through the center lens when he is within 9.5 minutes of arc of the glideslope, and is seen as level with the datum bars. As the aircraft moves more than 9.5 minutes of arc above or below the glideslope, the meatball is seen through higher or lower Fresnel lenses to give the appearance of moving vertically above or below the line of the datum bars (Figure 1).

For a carrier approach the pilot attempts to follow a designated glideslope (usually 3.5°), by keeping the meatball level with the datum bars, so that a hook attached to the tail of the aircraft will contact the landing deck midway between the second and third of four arrestment cables, known as wires. The wires are stretched across the landing deck at different distances from the ramp (threshold of the landing deck). Under the aircraft's momentum the hook travels forward to snag the third wire for a trap (arrested landing). The first or second wire may be caught on a low approach, and the fourth on a high approach. Very low approaches can result in a ramp strike (collision with the stern of the carrier) while high approaches can result in a bolter (a missed approach because of touchdown beyond the wire arrestment area).

The displacement information provided by the FLOLS is helpful for glideslope control but is less than optimum (Brictson, 1967; Durand, Tulvio, and Wasicko, 1967; Perry, 1968). Because the information from the meatball is of zero-order (displacement only), there are substantial lags between incorrect control inputs and the subsequent error information from the FLOLS. For example, a rate (first-order) error must exist for some short period of time before it produces a perceptible displacement (zero-order) error. The pilot is more directly in control of rate than of displacement, so that he could correct the rate error if he were aware of it before a substantial displacement error had developed. One popular technique for enhancing tracking performance, known as quickening, is to add to the displayed error one or more of its derivatives (Jensen, 1979; McCormick, 1970; Clement, McRuer and Klein, 1972). This can enhance tracking performance by reducing the delay between system response and displayed system error.

A normal quickening procedure would add a first-order component to the zero-order component that moves the meatball. This is not possible with the FLOLS as it is presently constructed, and would probably be undesirable because the pilot would no longer have unambiguous information about his position above or below the glideslope. This widely recognized disadvantage of quickening would be critical in carrier landing displays,

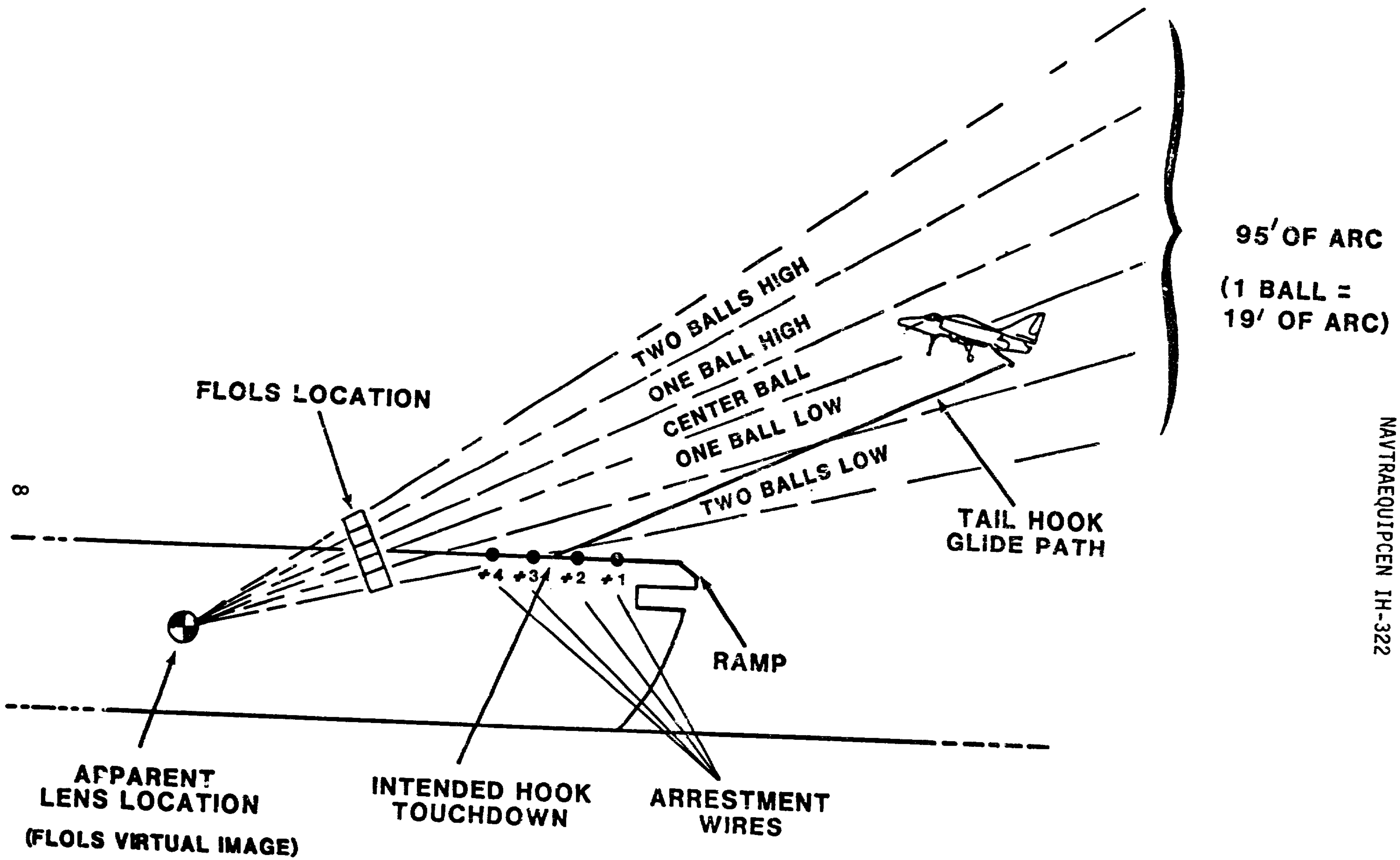


Figure 1. Carrier approach schematic depicting FLOLS envelope, tail hook glidepath, and arrestment wire locations.

particularly when the aircraft is nearing the ramp and touchdown. A quickened meatball could give the same indication whether the pilot were steady on glideslope or off glideslope but returning to it at an appropriate rate. At the ramp a low condition can be disastrous no matter how quickly the aircraft is returning to the glideslope. In addition, a quickened meatball could lead the pilot from a high condition at the ramp to the glideslope at touchdown, but at an excessive sink rate that would damage the aircraft.

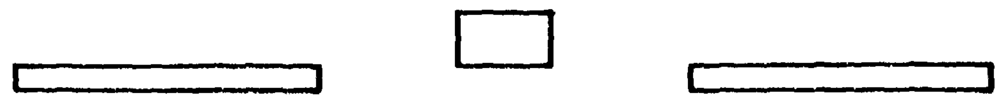
Although the desirability of improving the FLOLS display has long been recognized, it has remained essentially unchanged since its introduction into the fleet in the mid-1950's. At least two reasons can be readily cited to explain this fact. One has been discussed, that is, the possible adverse consequences of removing unambiguous displacement information presently provided by the meatball. This problem could be avoided by adding another element to the display, thereby providing additional information with no loss of information presently available.

The second problem has been the lack of any low-cost practical means of generating and displaying the necessary information. Today, however, sensor technology is sufficiently advanced so that aircraft position can be determined accurately from the carrier, and rate information can be rapidly calculated and displayed to the pilot. Although the technical details of such a device are beyond the scope of the present report, it has been determined that a reliable system could be implemented at a relatively low cost. It was therefore recognized that a simulator evaluation of one or more candidate first-order display concepts would be an appropriate first step, before evaluating a prototype system in the field.

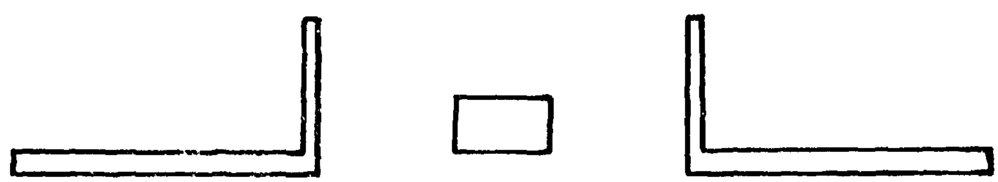
APPROACH

For this experiment, vertical light arrays appearing as bars or arrows extending up or down from the inside ends of the datum bars were added to the FLOLS to provide a first-order display. Two algorithms for driving the arrows were tested. One was a pure first-order algorithm that drove the arrows up or down depending on whether the meatball was moving up or down. Length of the arrows was proportional to the product of range and rate of meatball movement. This configuration was designated as the RATE display.

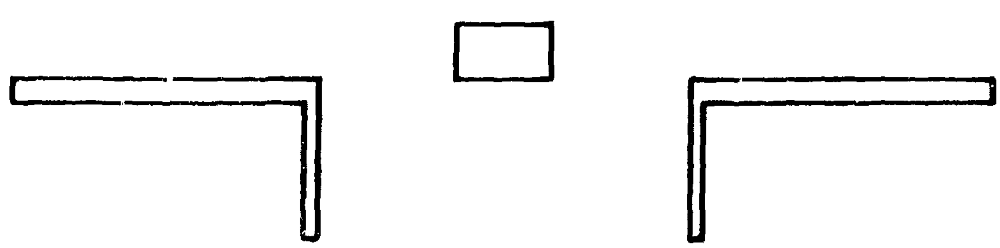
The other algorithm drove the arrows in proportion to the difference between the actual and the ideal descent rates so that null indications from the arrows would return the pilot to, or maintain him on, the glideslope. The arrows extended up when the descent rate was too low and down when it was too high. This configuration, which would be a type of quickened display if the meatball were not present, was designated the COMMAND display. While on glideslope, indications from the RATE and COMMAND displays were identical. When off glideslope, the COMMAND display indicated a return to the glideslope at an appropriate rate when the arrows were nulled (Figure 2).



(a) A static CONVENTIONAL display does not permit a trend interpretation. For the RATE display this figure indicates that the one-ball high condition will be maintained, while for the COMMAND display that the pilot is returning to the reference glideslope at an appropriate rate.



(b) For the RATE display this figure indicates one-ball high and going higher in relation to the reference glideslope. For the COMMAND display, it indicates that the aircraft is high, and is not returning to the glideslope quickly enough (and may even be going higher).



(c) For the RATE display this figure indicates that the pilot is returning to the glideslope, while for the COMMAND display that he is returning to it too quickly and will probably fly through it.

Figure 2. Three representations of possible RATE or COMMAND displays. Figure 2(a) can also represent a CONVENTIONAL display.

Care was taken to calibrate the command signal so that it would direct pilots to return to the correct glideslope as quickly as practicable. In contrast to most pilots who are content to converge on the desired runway aiming point with a slightly higher- or lower-than-specified glideslope, pilots who land on carriers consider it important to be on the correct glideslope at some distance from the ramp and to maintain a stable aircraft attitude and descent rate from there to touchdown. Glideslope deviations at the runway threshold that would be of little consequence for most landings on an airfield could result in a missed approach or a ramp strike in carrier operations. Attempts to correct glideslope errors close to the ramp are discouraged because neither the pilot nor the Landing Signal Officer (LSO) monitoring the approach can be confident that late corrections would result in a safe landing. An LSO will normally wave off an approach if he detects a substantial glideslope error when the aircraft is close to the ramp. Thus a command signal that encouraged a gradual return to the glideslope and allowed small but noticeable errors to touchdown would be acceptable and probably preferable in most airfield approaches, but would not be acceptable for carrier operations.

The relative merits of the two first-order configurations were difficult to assess analytically. The RATE display had first been proposed as a means of unburdening the pilot of the need to estimate the rate of the ball movement. Pilots occasionally comment that they seek to do that by glancing at the Vertical Speed Indicator (VSI), but further comment that it becomes increasingly difficult to glance at instruments inside the cockpit as they close on the carrier. The RATE display provided information similar to that from the VSI, but at a location that did not require the pilot to modify the recommended scan of the FLOLS, lineup cues, and Angle-of-Attack (AOA) indexer.

The COMMAND display was proposed as a means of further unburdening the pilot of the need to decide how quickly he should return to the glideslope. It also permitted the pilot to concentrate mostly on the arrows, thereby largely avoiding the problem of combining information from diverse display elements. However, the COMMAND display might have encouraged pilots to ignore the ball entirely. Any tendency for them to use the arrows exclusively might produce the previously discussed potential problems of the traditional quickened display. Another potential problem with either or both augmented displays was the possibility that pilots would fixate on the glideslope information, thereby disrupting their scan and paying too little attention to lineup and AOA control. As no clear preference for either configuration could be established, both were evaluated, as well as the standard FLOLS referred to here as the CONVENTIONAL display.

The difficulties of landing on carriers are accentuated by marginal weather and at night. For example, boarding rates are lower at night and most accidents from ramp strikes, excessive sink rates, and missed approaches occur at night. The modified FLOLS might not affect the high boarding rates achieved on calm days but could substantially affect night and marginal weather performance. Thus turbulence and time-of-day factors were included in the experiment as independent variables to examine a variety of flying conditions.

SECTION II

METHOD

SUBJECTS

Eight experienced carrier-qualified Navy pilots made carrier landings in a flight simulator at the Naval Training Equipment Center (NAVTRAEQUIPCEN). Table 1 summarizes the flight experience of the pilots.

APPARATUS

The Visual Technology Research Simulator (VTRS) consists of a fully instrumented T-2C Navy jet trainer cockpit, a six degree-of-freedom synergistic motion platform, a 32-element G-seat, a wide angle visual system that can project both computer generated and model board images, and an Experimenter/Operator Control Station (Collyer and Chambers, 1978). The motion system, G-seat and model board were not used in this experiment.

Visual System

The background subtended 50° above to 30° below the pilots eye level, and 80° to either side of the cockpit. The carrier image, which was a representation of the Forrestal (CVA 59), was generated by computer and projected onto the background through a 1025-line video system. A carrier wake and FLOLS were also generated by this method. Both daytime and nighttime carrier images were displayed (Figures 3 and 4).

Average delays between control inputs and generation of the corresponding visual scene were approximately 116 msec. Calculation of new aircraft coordinates required 66 msec while generation of the visual scene corresponding to the viewpoint from the new aircraft coordinates required approximately 50 msec. An updated visual scene was displayed every 33 msec.

The sky brightness for the day scene was 1 fL (foot-Lambert) and the seascape brightness was 0.4 fL. The brightest area of the day carrier was 2.2 fL. Except for the horizon there were no features represented in either the sky or sea. The night background luminance was 0.04 fL and the horizon and seascape were not visible. The night carrier appeared as lights of 1 fL brightness outlining the landing deck and other features.

Fresnel Lens Optical Landing System

The configuration of the FLOLS is shown in Figure 5. In contrast to a carrier FLOLS, which is generated by incandescent lights, and can therefore be much brighter than other parts of the carrier, the simulated FLOLS was generated by the same system as the carrier image. It

TABLE 1. BIOGRAPHICAL DATA ON PILOT SUBJECTS

Subject #	1	2	3	4	5	6	7	8
Age	29	32	26	28	36	25	26	26
Flight Hours (Military)								
Aircraft	1475	2075	1905	1300	2250	505	675	1160
Simulator	400	220	140	140	150	95	210	175
Last 30 Days Hours/Aircraft	20/A7	15/A7	35/S3	30/S3	20/A7	25/A7	30/A7	25/A7
Number of Traps								
Total	290	350	140	115	700	115	140	174
Last 12 Months	100	0	90	5	140	90	130	110
Last 30 Days	0	0	0	0	0	0	0	0

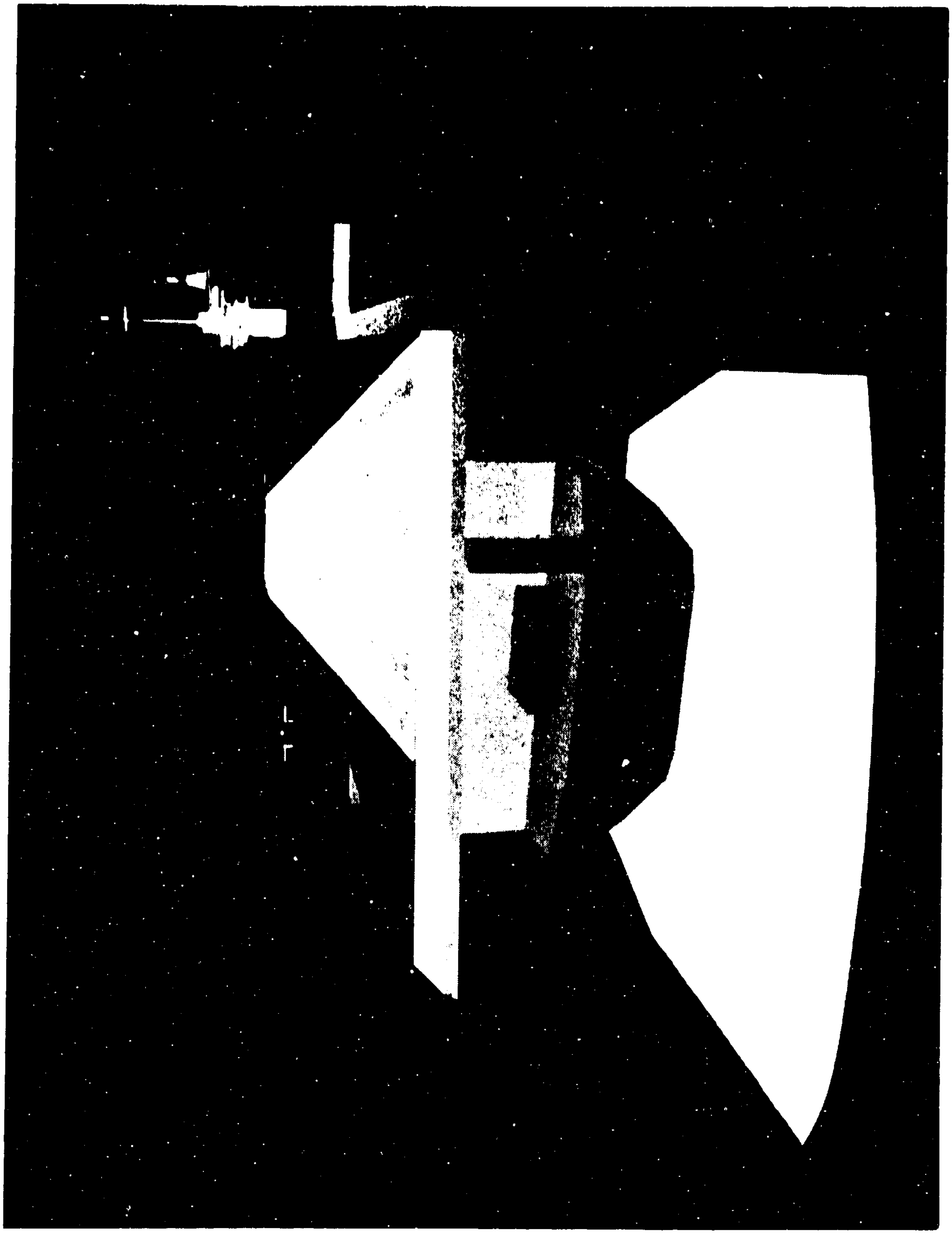


Figure 3. Computer-generated image of the day carrier, with FLOLS and portion of wake.

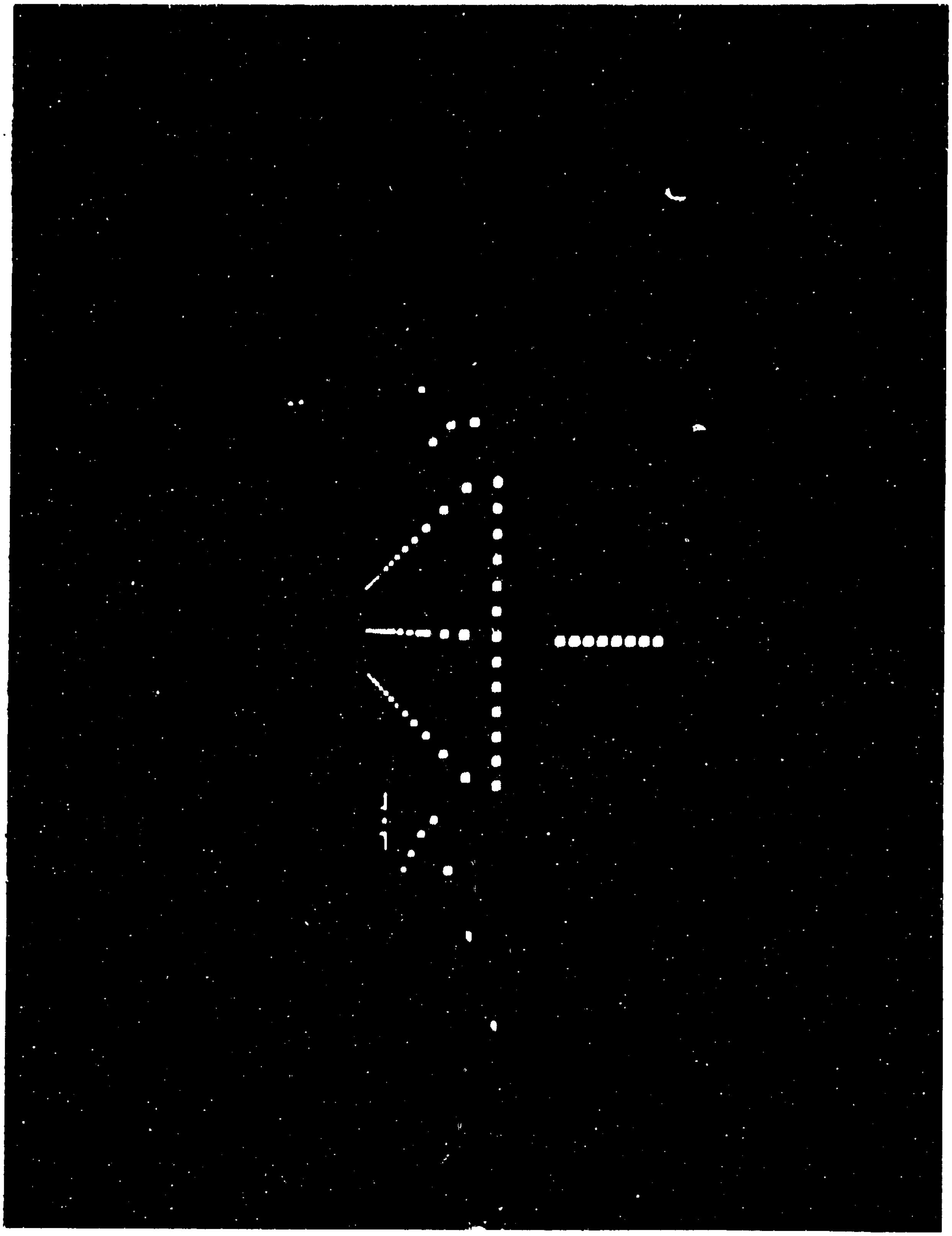


Figure 4. Computer-generated image of the night carrier, with FLOLS.

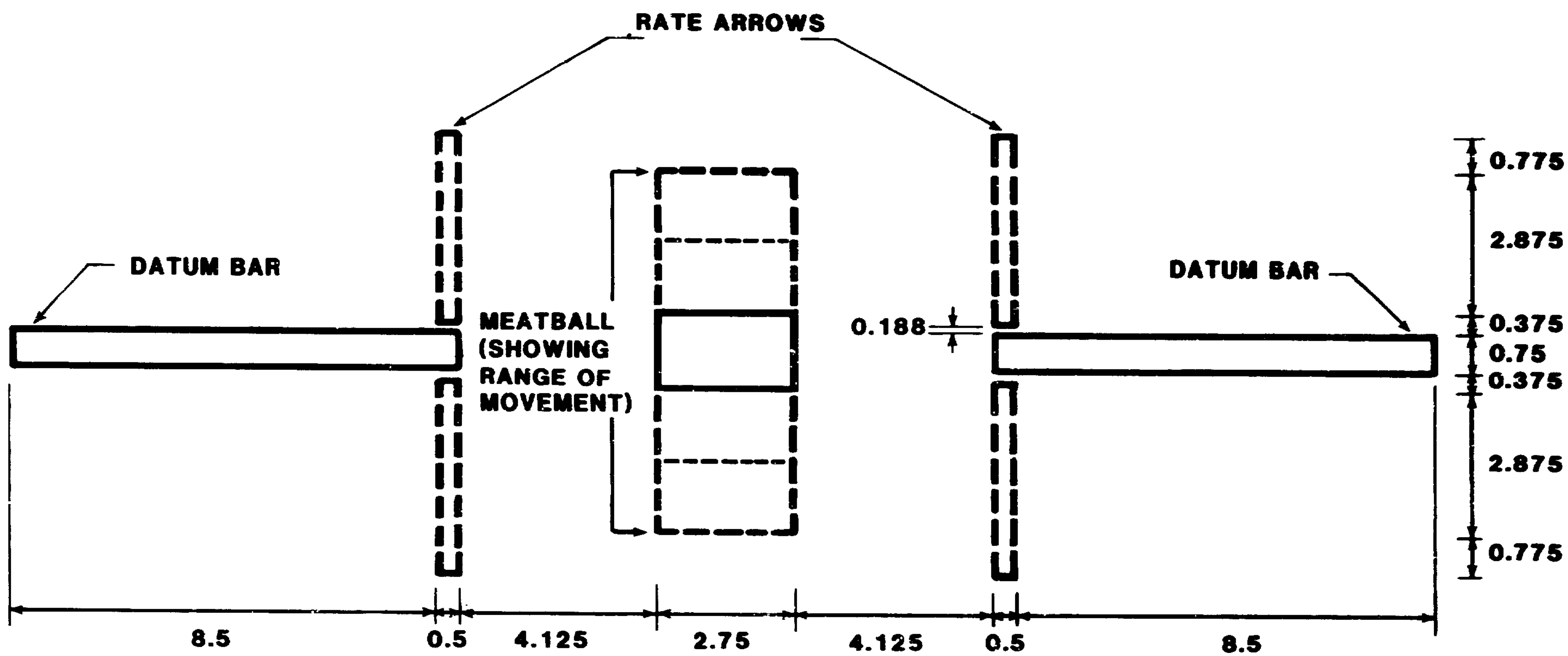


Figure 5. Configuration of FLOLS simulation, showing datum bars, rate arrows, and meatball. (dimensions shown are in ft.)

was therefore only as bright as the brightest areas of the ship (e.g., the white lines on the landing deck). To compensate for its lower relative brightness, the FLOLS was enlarged by a factor of three when the distance behind the ramp was greater than 2250 ft. From 2250 ft. the size of the FLOLS was linearly reduced until it attained its normal size at 750 ft. It remained its normal size throughout the remainder of the approach. The FLOLS was centered 414 ft. down the landing deck and 61 ft. to the left of the centerline. It was set at a nominal 3.5° glideslope and with a lateral viewing wedge of 52°.

Display Dynamics

The two augmented displays simulated in the experiment differed only in terms of their response dynamics and corresponding drive algorithms, and were otherwise identically configured. The augmented feedback elements of the displays (i.e., the arrows) were simply added to the conventional FLOLS arrangement, without altering its basic characteristics (Figure 5).

RATE Display. The first augmented FLOLS display included direct first-order feedback in addition to the displacement information of the conventional FLOLS. The RATE arrows were proportional to the difference between the aircraft's actual descent rate and the descent rate that would maintain its present glideslope angle with respect to the FLOLS. Specifically, this display provided a continuous indication of the component of the aircraft velocity vector that is perpendicular to slant range, r_L (Figure 6). The length of the arrows (l_a) was determined as follows:

$$l_a = k_o \dot{s}$$

and

$$\dot{s} = r_{L_i} \left[\frac{(\Theta_{e_i} - \Theta_{e_{i-1}})}{\tau} \right] \frac{2\pi}{360}$$

where $\dot{s}$ = rate of aircraft displacement perpendicular to r_L (ft./sec

r_{L_i} = current slant range of aircraft from FLOLS virtual image (ft.)

Θ_{e_i} = current angular displacement of aircraft from nominal glideslope (deg.)

$\Theta_{e_{i-1}}$ = angular displacement of aircraft from nominal glideslope at previous simulation sampling period (deg.)

k_0 = 0.63; arrow scale factor

τ = .033 sec; the duration between simulation sampling points

and $\frac{2\pi}{360}$ = conversion constant from degrees to radians.

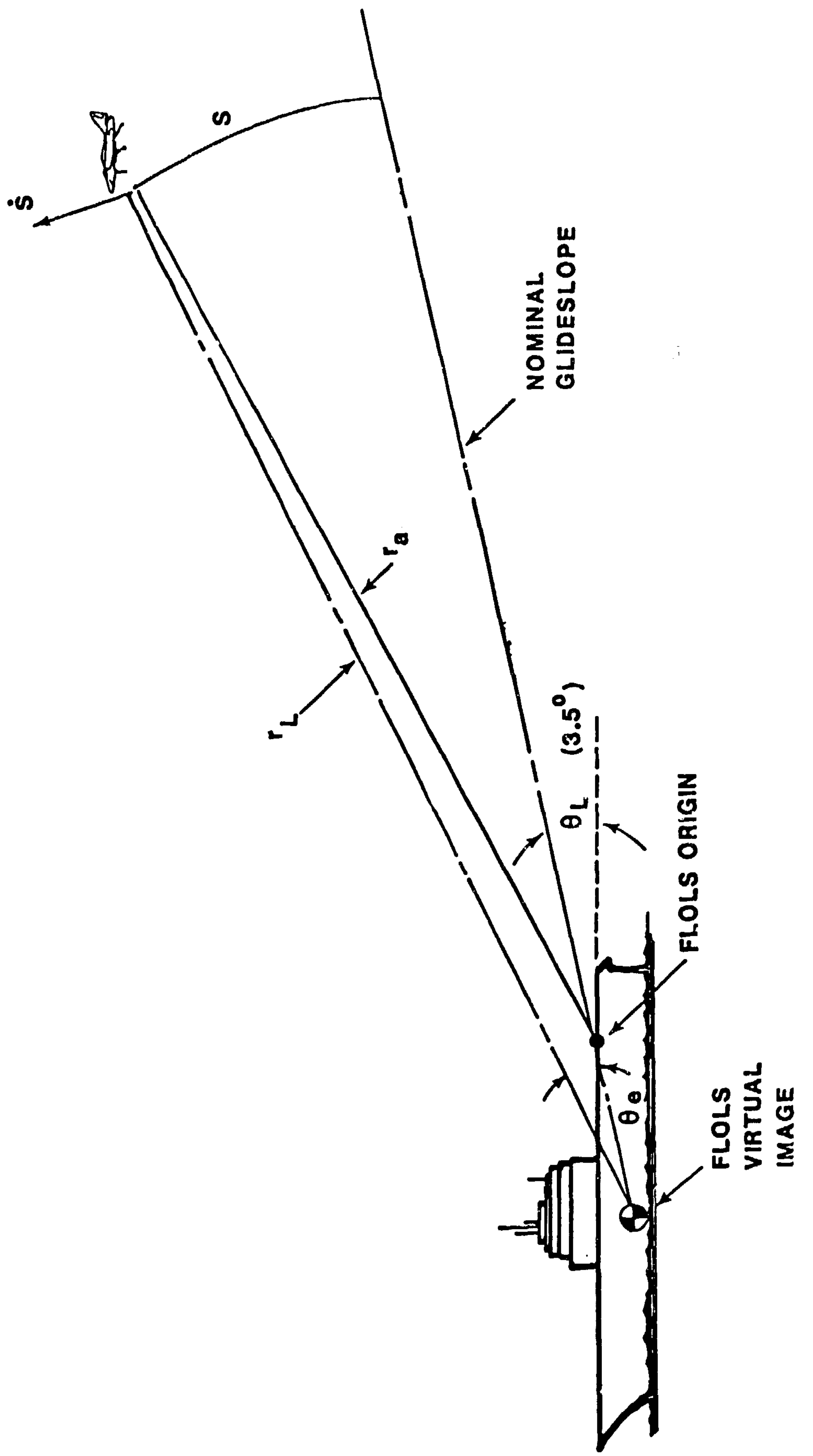


Figure 6. RATE Display Nomenclature

The effect of this computation was to present the first-order information to the pilot on a linear scale (ft./sec.), while the zero-order information provided by the conventional FLOLS meatball continued to be presented on an angular scale (deg.) This resulted in the arrows having the same sensitivity to glideslope displacement rates at any point during the approach, while the meatball became increasingly sensitive to small changes as the aircraft approached the carrier. Full-scale extension of the arrows was achieved with a rate of ±6.4 ft./sec., which corresponded to approximately ±4.03 scale ft. vertical displacement of the arrows from the datum bars.

COMMAND Display. The second augmented display simulated in the experiment contained the zero-order position information and additional vertical arrows as in the RATE display, but differed in that it provided the higher-order system response elements according to a "command"-type drive algorithm. The length of the arrows was proportional to the difference between the glideslope displacement rate, $\dot{s}$ (as described previously), and a commanded rate which was a function of displacement. For a given aircraft velocity, range and glideslope deviation, the command function specified a unique curved trajectory in the vertical plane that would smoothly guide the pilot back to the glideslope. The length of the arrows, l_a, was proportional to $\dot{s}_e$, the glideslope displacement rate error signal:

$$l_a = k_0\, \dot{s}_e \text{ (where } k_0 = 0.63\text{, as before)}$$

and $$\dot{s}_e = \dot{s} - \dot{s}_c$$

where $\dot{s}_c$ (shown graphically in Figure 7) is the commanded displacement rate, calculated from:

$$\dot{s}_c = k_1 s + b \text{ for } |s| \geq w$$

$$= 0 \quad \text{for } |s| < w$$

where s = aircraft displacement perpendicular to r_L (ft.)

$$= r_L\, \Theta_e \cdot \frac{2\pi}{360}$$

k_1 = -0.15; a constant, first derived analytically and then adjusted empirically during pre-experimental work

b = $-k_1 w$ for $s \leq -w$

= $+k_1 w$ for $s \geq w$

and w = one-half the extent of a dead band around the nominal glideslope within which the COMMAND dynamics were identical to those for the RATE display.

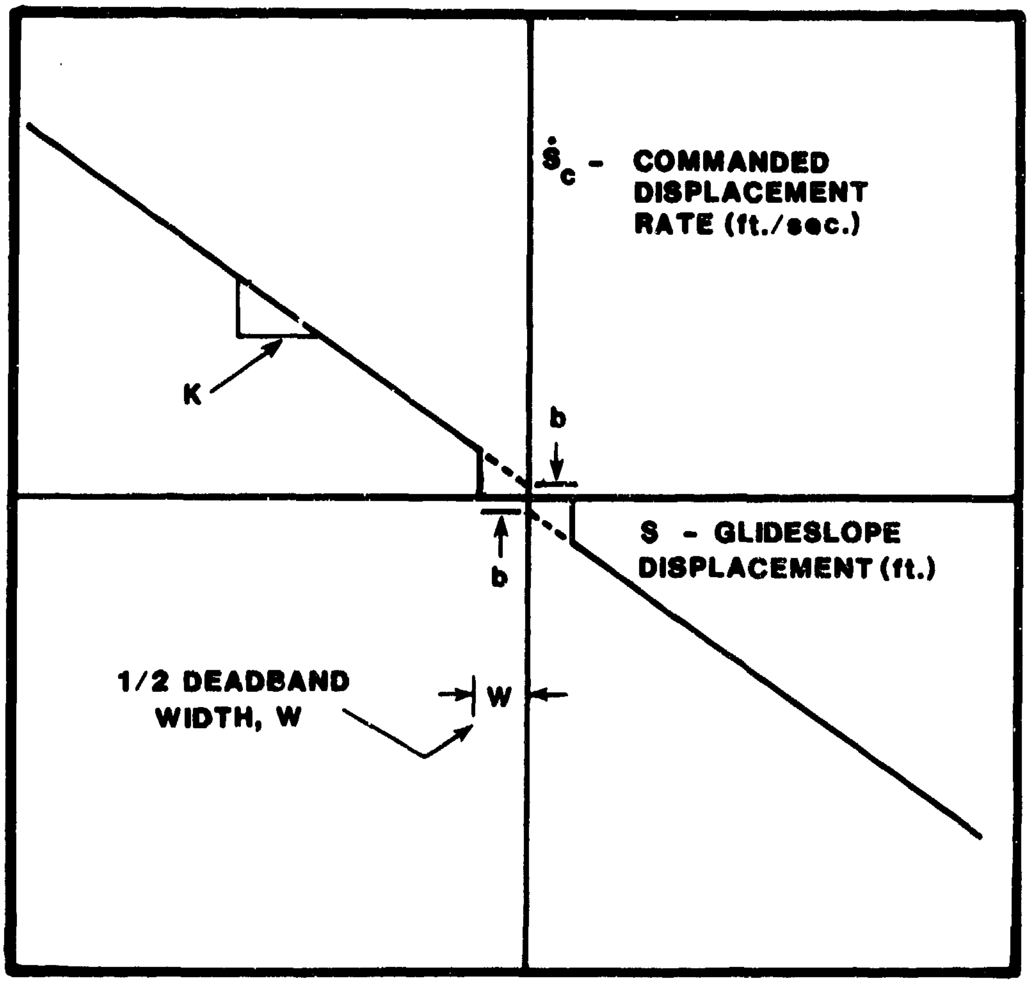


Figure 7. Shape of Command Function (not drawn to scale).

The dead band of width 2w was introduced to prevent error signals from inducing overshoot or overcontrolled conditions during the final seconds of the approach. During pre-experimental work, w was set to 3.0 ft., but that figure appeared excessive during trials with the first two subjects, and was reduced to 1.0 ft. for the remaining six subjects.

Simulator Configuration

The simulator was initialized with the aircraft at 9000 ft. from the ramp, on the glideslope and centerline, and in the approach attitude and configuration (hook and wheels down, speed brake out, 15 units AOA, and power at 83%). The T-2C is normally landed with full flaps, but flaps were set at half extension for this experiment to more closely simulate approach speeds of typical fleet aircraft (approximately 130 knots in this case). Fuel was set at 1320 lbs to give 10,000 lbs gross weight. A landing trial was flown from the initial condition to wire arrestment or, in the case of a bolter, to 1000 ft. past the carrier.

The carrier was set on a heading of 360° at 20 knots. Environmental wind was set at 317° with a velocity of 6.34 knots. This combination of carrier speed and environmental wind produced a relative wind component of 25.02 knots at .56° relative to the landing deck, which was canted at 10.5°. Thus the effective right-to-left crosswind component was 0.25 knot.

Turbulence was used as an independent difficulty factor. The turbulence model buffeted the simulator in the vertical axis with a random forcing function, having a Root Mean Square value of 2.0 ft/sec.

PROCEDURE

Pilots flew 122 approaches over a three day period. On their first day, they were briefed on the purpose and conditions of the experiment. They were instructed in safety procedures for the simulator and in its features that did not represent aircraft functions. They then flew the simulator for five minutes without attempting to land. They completed their familiarization period with twenty approach trials using the CONVENTIONAL display. The first ten approaches were flown under the Day/No Turbulence condition, the next five under the Day/Turbulence condition and the last five under the Night/No Turbulence condition. For these practice trials pilots were asked to land using their normal techniques.

On their second day, pilots flew two 34-trial blocks with a two-hour rest between blocks. They finished the experiment on their third day with another 34-trial block. Each block lasted approximately two hours with each landing trial taking approximately 50 seconds, and set-up time between trials taking approximately two minutes. A ten-minute rest was inserted after the sixteenth trial of each block.

The subjects flew all four combinations of Turbulence and Time of Day with each FLOLS type. The design, detailed in Table 2, counterbalanced for trends across and within blocks, and used buffer trials to

TABLE 2. EXPERIMENTAL DESIGN

FAMILIARIZATION BLOCK - ALL SUBJECTS

FLOLS Drive	CONVENTIONAL		
Trial #	1-10	11-15	16-20
Environment	1	2	3

EXPERIMENTAL BLOCK #1 - SUBJECT #1

FLOLS Drive	C O N-			10 min.	V E N T I O N A L						
Trial #	1-10 (Practice)	11-16			17-22		23-28		29-34		
Environment	1	2	2		3	3	1	1	4	4	

Trials 11, 12, 17, 18, 23, 24, 29, 30 to dissipate proactive interference from prior environmental condition

FLOLS DRIVE AND ENVIRONMENTAL CONDITION SEQUENCES - ALL SUBJECTS

Subject #	Block #	1	2	3
1	FLOLS Drive	CONVENTIONAL	RATE	COMMAND
	Environment	1 2 3 1 4	1 4 3 2 1	1 1 2 4 3
2	FLOLS Drive	RATE	COMMAND	CONVENTIONAL
	Environment	1 3 1 4 2	1 2 4 1 3	1 3 4 2 1
3	FLOLS Drive	COMMAND	CONVENTIONAL	RATE
	Environment	1 1 2 3 4	1 4 1 3 2	1 2 3 1 4
4	FLOLS Drive	COMMAND	RATE	CONVENTIONAL
	Environment	1 4 3 2 1	1 1 2 4 3	1 3 1 4 2
5	FLOLS Drive	CONVENTIONAL	COMMAND	RATE
	Environment	1 2 4 1 3	1 3 4 2 1	1 1 2 3 4
6	FLOLS Drive	RATE	CONVENTIONAL	COMMAND
	Environment	1 4 1 3 2	1 2 3 1 4	1 4 3 2 1
7	FLOLS Drive	CONVENTIONAL	RATE	COMMAND
	Environment	1 2 3 1 4	1 4 3 2 1	1 1 2 4 3
8	FLOLS Drive	COMMAND	RATE	CONVENTIONAL
	Environment	1 4 3 2 1	1 1 2 4 3	1 3 1 4 2

Environment Code: Day/No Turbulence = 1 Night/No Turbulence = 3
Day/Turbulence = 2 Night/Turbulence = 4

counter possible learning effects between experimental conditions.

Transition from one FLOLS type to another was thought to provide a serious potential for disruptive learning effects. Thus FLOLS types were varied only across 34-trial blocks with the first 10 trials of each block used to familiarize pilots with that FLOLS type and to dissipate the effects of flying with a different FLOLS type in the previous block. The remaining 24 trials were divided into four sub-blocks of six trials in which pilots flew under the four combinations of environmental conditions. As interference between conditions was considered a possibility, the first two trials of each sub-block were used to dissipate any effects from the previous environmental condition. The data to be presented here are from the last four trials of each six-trial sub-block.

PERFORMANCE MEASUREMENT AND DATA ANALYSIS

Parameters of aircraft position and attitude were sampled at 30 Hz and used to derive altitude and lineup error scores from the desired approach path, and deviations from desired AOA (15 units). Root Mean Square (RMS) error, mean algebraic error and variability around that mean were calculated for these three dependent variables over four equal segments of the final 6000 feet of the approach.

Because the trends obtained with the three types of dependent measures were generally similar, RMS error scores are used to illustrate the results. Algebraic lineup error scores are used to illustrate one lineup trend that was not evident from the RMS error scores. Altitude and lineup errors at 4500, 3000, 2000, 1000, and 0 ft. from the ramp were used to derive means and standard deviations at these five points in the approach across display conditions. Distance down the deck, distance from the centerline, and descent rate were measured at touchdown, and the Landing Performance Score (LPS) (Brictson, Burger, & Wulfeck, 1973) was calculated. The LPS is a score assigned to each pass, ranging from 1.0 (technique waveoff) to 6.0 (#3 wire trap).

Lateral stick, longitudinal stick, rudder pedal, and throttle positions were sampled at 30 Hz. The distance of control movement from one sampling point to the next was accumulated over one-second periods and averaged over segments of 6000 to 1600 feet, 1600 to 400 feet, and 400 to 0 feet from the ramp.

At completion of the trials, the pilot subjects and two Landing Signal Officers (LSOs) who had attended to score approaches during the first week of testing responded to a questionnaire on their attitudes toward the FLOLS displays. They were specifically requested to indicate their relative preferences for the displays.

Repeated measures analysis of variance was used as the primary statistical test of trends in the data. Reliable FLOLS main effects were further tested with the three possible pairwise comparisons. Eta squared was used to estimate the proportion of variance accounted for by reliable effects. Differences in variability between the FLOLS displays, as shown by the standard deviations of error scores recorded at 4500, 3000, 2000, 1000 and 0 ft. from the ramp, were examined with the Bartlett test for homogeneity of variance. Where the Bartlett test indicated statistical reliability, a test for homogeneity of variance described by Winer (1971, p.205) was used for the pairwise comparisons.

SECTION III

RESULTS

Tables 3, 4 and 5 show means of main effects for RMS glideslope, lineup and AOA error over four segments of the approach beginning 6000 ft. behind the ramp. The tables also present statistical reliabilities for main effects, interactions and pairwise comparisons, and values of eta squared (η^2) for reliable effects (eta squared represents the proportion of total variability in the data that is accounted for by a particular effect).

FLOLS type had a consistent and reliable effect on glideslope error throughout the approach, with the most substantial contribution to this effect coming from the superiority of the COMMAND to the CONVENTIONAL display (Table 3). This pairwise comparison was statistically reliable throughout the approach and accounted for approximately 10% of the experimental variance in each approach segment. The pairwise comparisons also showed landing performance to be reliably better with the COMMAND than with the RATE display over the two 1500-ft. segments from 6000 to 3000 ft. from the ramp and reliably better with the RATE than with the CONVENTIONAL display over the 6000- to 4500-ft. segment.

Glideslope RMS error scores increased in the presence of turbulence, an effect that was statistically reliable throughout the approach. However, only in the latter part of the approach did the effect account for a substantial portion of the experimental variance. Only two interactions were reliable and both accounted for only trivial portions of the experimental variance.

There were no statistically reliable effects for lineup RMS error (Table 4). The only effect on lineup performance was an unexpected time-of-day effect on lineup bias. There was a consistent tendency for pilots to fly day approaches about 0.2° to the right. Although a lineup deviation of 0.2° could probably not be considered operationally significant, the effect was strong in that it accounted for approximately 10% of the experimental variance.

The effect of turbulence on AOA RMS error was the only statistically reliable AOA effect throughout the approach (Table 5), and was substantial in that it accounted for approximately 50% of the experimental variance.

Figures 8 and 9 show means and standard deviations of glideslope and lineup errors with the three FLOLS types sampled at 4500, 3000, 2000, 1000 and 0 ft. from the ramp. These figures were drawn from the data of Table 6. Figure 8 indicates that pilots flew further above the glideslope with the CONVENTIONAL than with the RATE display while with the COMMAND display they tended to fly slightly below the glideslope. These bias differences between the CONVENTIONAL and COMMAND displays were reliable at all sampling points and between the CONVENTIONAL and

TABLE 3. GLIDESLOPE RMS ERROR (IN FEET): MEANS, STATISTICAL RELIABILITIES (*:$p<.05$, **:$p<.01$), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM THE RAMP (FT)	6000-4500	4500-3000	3000-1500	1500-0
MEANS				
FLOLS TYPE (FL)				
Conventional (CONV)	14.74	13.83	10.83	6.09
Rate (RATE)	11.97	10.81	8.08	4.61
Command (COMM)	7.84	6.98	5.27	3.67
TIME OF DAY (Ti)				
Night	12.91	11.02	8.13	4.81
Day	10.12	10.06	7.98	4.77
TURBULENCE (Tu)				
Turbulent	8.26	7.89	6.29	4.29
Calm	7.42	6.06	4.25	3.06

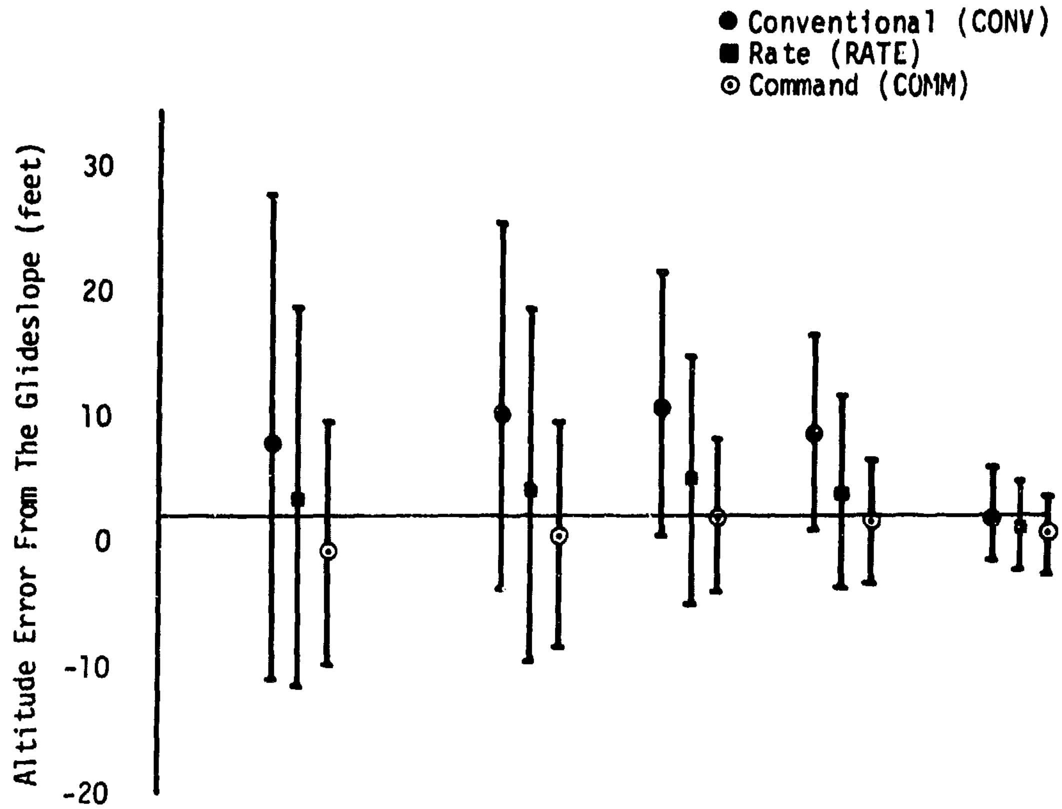
RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2	p	η^2
FL	**	.106	**	.111	**	.124	*	.096
CONV vs RATE	*	.017	-	-	-	-	-	-
CONV vs COMM	**	.105	**	.110	**	.124	**	.095
RATE vs COMM	**	.038	*	.059	-	-	-	-
Ti	*	.026	-	-	-	-	-	-
Tu	**	.017	**	.020	**	.034	**	.085
FL x Ti	-	-	-	-	*	.001	-	-
FL x Tu	-	-	-	-	-	-	*	.005
Ti x Tu	-	-	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-	-	-

TABLE 4. LINEUP RMS ERROR (IN FEET): MEANS, STATISTICAL RELIABILITIES (*:$p<.05$, **:$p<.01$), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM THE RAMP (FT)	6000-4500		4500-3000		3000-1500		1500-0	
MEANS								
FLOLS TYPE (FL)								
Conventional (CONV)	29.35		24.44		15.56		8.28	
Rate (RATE)	24.77		20.18		13.98		7.42	
Command (COMM)	23.68		21.05		16.14		8.84	
TIME OF DAY (Ti)								
Night	24.95		20.12		14.12		8.10	
Day	26.91		23.66		16.33		8.25	
TURBULENCE (Tu)								
Turbulent	25.77		23.37		17.61		9.75	
Calm	21.58		18.74		14.67		7.92	
RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2	p	η^2
FL	-	-	-	-	-	-	-	-
CONV vs RATE								
CONV vs COMM								
RATE vs COMM								
Ti	-	-	-	-	-	-	-	-
Tu	-	-	-	-	-	-	-	-
FL x Ti	-	-	-	-	-	-	-	-
FL x Tu	-	-	-	-	-	-	-	-
Ti x Tu	-	-	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-	-	-

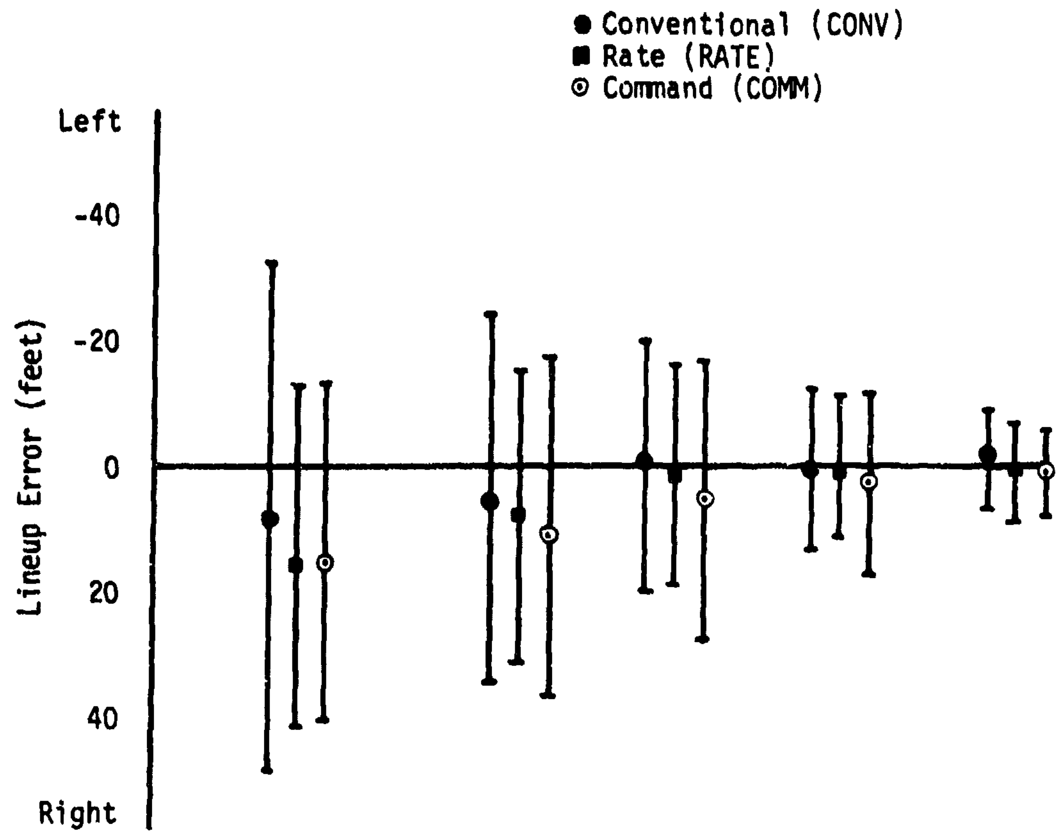
TABLE 5. ANGLE OF ATTACK RMS ERROR (IN AOA UNITS): MEANS, STATISTICAL RELIABILITIES (*:$p<.05$, **:$p<.01$), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM RAMP (FT)	6000-4500		4500-3000		3000-1500		1500-0	
MEANS								
FLOLS TYPE (FL)								
Conventional (CONV)	0.667		0.674		0.660		0.786	
Rate (RATE)	0.698		0.649		0.638		0.764	
Command (COMM)	0.663		0.672		0.688		0.793	
TIME OF DAY (Ti)								
Night	0.674		0.664		0.641		0.764	
Day	0.677		0.666		0.683		0.748	
TURBULENCE (Tu)								
Turbulent	0.906		0.899		0.889		1.014	
Calm	0.445		0.431		0.435		0.548	
RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2	p	η^2
FL	-	-	-	-	-	-	-	-
CONV vs RATE								
CONV vs COMM								
RATE vs COMM								
Ti	-	-	-	-	-	-	-	-
Tu	**	.496	**	.539	**	.550	**	.477
FL x Ti	-	-	-	-	-	-	-	-
FL x Tu	-	-	-	-	-	-	-	-
Ti x Tu	-	-	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-	-	-



Distance from Ramp (ft)		4500	3000	2000	1000	0
Reliabilities of Differences Between:						
Means	CONV vs RATE	-	*	**	**	-
	CONV vs COMM	**	**	**	**	*
	RATE vs COMM	-	-	-	-	-
s.d.'s	CONV vs RATE	**	-	-	-	-
	CONV vs COMM	**	**	**	**	**
	RATE vs COMM	**	**	**	**	**

Figure 8. Glideslope errors (means and standard deviations), and reliabilities of differences across FLOLS type (*:p<.05, **:p<.01).



		4500	3000	2000	1000	0
Distance from Ramp (ft)		4500	3000	2000	1000	0
Reliabilities of Differences between:						
Means	CONV vs RATE	-	-	-	-	-
	CONV vs COMM	-	-	-	-	-
	RATE vs COMM	-	-	-	-	-
s.d.'s	CONV vs RATE	**	**	-	*	-
	CONV vs COMM	**	-	-	-	**
	RATE vs COMM	-	*	**	**	**

Figure 9. Lineup errors (means and standard deviations), and reliabilities of differences across FLOLS type (*:p<.05, **:p<.01).

TABLE 6. GLIDESLOPE AND LINEUP ERRORS: MEANS (AND STANDARD DEVIATIONS) ACROSS FLOLS TYPE.

DISTANCE FROM RAMP (FT)	4500	3000	2000	1000	0
GLIDESLOPE ERROR (+ = HIGH)					
Conventional	5.33 (17.49)	7.27 (13.28)	7.94 (9.69)	5.91 (6.60)	-0.12 (3.40)
Rate	1.72 (13.97)	1.92 (12.65)	2.46 (9.02)	1.69 (6.47)	-0.90 (3.39)
Command	-2.22 (8.56)	-1.64 (8.28)	0.02 (5.54)	0.43 (4.29)	-1.62 (2.94)
LINEUP ERROR (+ = RIGHT)					
Conventional	7.69 (36.49)	4.57 (26.96)	-0.26 (18.10)	0.20 (11.78)	-0.71 (7.39)
Rate	12.96 (26.54)	6.52 (20.36)	1.45 (15.89)	1.32 (9.67)	0.66 (7.19)
Command	11.80 (26.41)	9.14 (24.18)	4.50 (19.92)	2.65 (13.12)	0.65 (5.67)

RATE displays at 3000, 2000, and 1000 ft. The bias differences between the RATE and COMMAND displays were not reliable.

Glideslope tracking performance was reliably less variable (as indicated by the standard deviations) for the COMMAND than for either of the other displays at all ranges. It was reliably less variable with the RATE than with the CONVENTIONAL display only at 4500 ft. Glideslope stability is critical at the ramp insofar as it reduces the probability of a ramp strike. The distribution of glideslope errors at the ramp reflected the greater stability of glideslope performance with the COMMAND display; the lowest COMMAND approach error of seven feet below the glideslope was exceeded twice with the CONVENTIONAL display (two eight foot errors) and twice with the RATE display (errors of eight and ten feet).

As may be seen from Figure 9 and Table 6, lineup variability was generally highest for the CONVENTIONAL display and lowest for the RATE, although not all pairwise comparisons were reliable. At the ramp, however, the COMMAND display reliably produced the most stable lineup scores.

Touchdown scores are summarized in Tables 7 and 8. FLOLS type had a statistically reliable effect on LPS, with the COMMAND display giving a higher score (indicating better performance) than the CONVENTIONAL or the RATE displays. Descent rate was reliably lower for the COMMAND than for either the CONVENTIONAL or RATE displays, and was closer to the reference descent rate of 8.58 ft. per sec.

Standard deviations for distance from the ramp, distance from the centerline and descent rate were reliably smaller for the COMMAND than for the CONVENTIONAL display. In addition, distances from the ramp and centerline were reliably less variable with the COMMAND than with the RATE display.

Descent rate at touchdown is critical in that an excessive descent rate can damage the aircraft. As might be expected from the lower descent rate mean and standard deviation for the COMMAND display, the maximum COMMAND descent rate was not as high as the maximums for the other two displays (16 ft. per sec. versus 17 and 18 ft. per sec. for the CONVENTIONAL and RATE displays). The maximum for the RATE display exceeded the theoretically safe limit of 17.07 ft. per sec.

As bolter rates also affect the efficiency of carrier operations it is significant to note that the bolter rate obtained with the COMMAND display was one-half that of the CONVENTIONAL display. Out of 128 passes flown under each condition, there were 26 bolters (20%) with the CONVENTIONAL, 22 (17%) with the RATE, and 13 (10%) with the COMMAND display.

Some reliable effects at touchdown for time-of-day and for turbulence were also apparent. Both calm and night approaches resulted in a higher LPS. Distance from the ramp and descent rate were less variable

TABLE 7. TOUCHDOWN SCORES: MEANS, STATISTICAL RELIABILITIES (*:p<.05, **:p<.01), AND VALUES OF ETA SQUARED (η^2).

	LPS	Distance Down Deck (feet)	Distance From Centerline (feet)	Descent Rate (ft. per sec.)
Reference Values for ideal approach	6.0	194.5	0	8.58
MEANS				
FLOLS TYPE (FL)				
Conventional (CONV)	4.29	188	-0.76	9.46
Rate (RATE)	4.47	176	0.49	9.44
Command (COMM)	4.77	180	0.51	8.63
TIME OF DAY (Ti)				
Night	4.71	173	-0.22	9.64
Day	4.30	140	0.38	8.71
TURBULENCE (Tu)				
Turbulent	4.28	181	0.05	9.40
Calm	4.74	182	0.11	8.95

RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2	p	η^2
FL	*	.021	-	-	-	-	*	.027
CONV vs RATE	-	-					-	-
CONV vs COMM	**	.022					*	.020
RATE vs COMM	-	-					*	.020
Ti	*	.012	-	-	-	-	-	-
Tu	**	.022	-	-	-	-	-	-
FL x Ti	-	-	-	-	-	-	-	-
FL x Tu	-	-	-	-	-	-	-	-
Ti x Tu	-	-	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-	-	-

TABLE 8. TOUCHDOWN SCORES: STANDARD DEVIATIONS AND STATISTICAL RELIABILITIES OF DIFFERENCES BETWEEN THEM (*:p<.05, **:p<.01)

	LPS	Distance Down Deck (feet)	Distance From Centerline (feet)	Descent Rate (ft. per sec.)
STANDARD DEVIATIONS				
FLOLS TYPE (FL)				
Conventional (CONV)	1.39	52.4	7.32	2.62
Rate (RATE)	1.39	50.7	6.91	2.28
Command (COMM)	1.18	40.1	5.18	2.09
TIME OF DAY (Ti)				
Night	1.21	44.0	7.29	2.05
Day	1.42	50.0	5.72	2.57
TURBULENCE (Tu)				
Turbulent	1.39	57.1	6.80	2.81
Calm	1.23	37.3	6.30	1.80
RELIABILITIES	p	p	p	p
FL	-	**	**	*
CONV vs RATE		-	-	-
CONV vs COMM		**	**	**
RATE vs COMM		**	**	-
Ti	*	-	**	**
Tu	-	**	-	**

for calm than for turbulent approaches while LPS and descent rate were less variable, and distance from the centerline more variable, for night than for day approaches.

None of the analyses of control activity (Tables B1 to B4 in Appendix B) showed reliable effects for FLOLS type. There was a reliable tendency for lateral stick and rudder pedal activity to be higher for night than for day approaches, but this effect accounted for only a small portion of the experimental variance. Longitudinal stick and throttle activity was reliably higher with turbulent than with calm atmospheric conditions and this effect accounted for approximately 5% of the experimental variance.

The results of the questionnaires completed by all eight pilot subjects and the two LSO observers provide very strong support for the first-order displays. All ten respondents said that use of the arrows would make carrier landings safer, especially at night. Nine out of ten preferred the COMMAND to the RATE display. Several commented that the arrows were of greatest benefit from the start to in-close, and that they were not sensitive enough from the in-close to at-the-ramp positions. Appendix C presents excerpts from the questionnaires, covering the general usefulness of the first-order displays, and providing some specific comments on the relative effectiveness of RATE versus COMMAND.

Finally, Table 9 is presented as a means of summarizing the significant findings of this experiment. It presents all nine measures for which there were statistically reliable differences due to FLOLS display type. To make possible a ready comparison of the size of the effect across different measures, scores presented are the percent improvement of RATE and COMMAND over the CONVENTIONAL display. To review the actual scores and levels of statistical reliability at various points during the approach, refer to the appropriate table or figure as indicated. Table 9 shows that for all measures for which there was a reliable display difference, performance was improved by use of the first-order displays. Additionally, the COMMAND display produced the greater improvement in every case except one (lineup variability).

TABLE 9. SUMMARY OF MEASURES SHOWING RELIABLE EFFECTS OF FLOLS DISPLAY TYPE. DATA ARE PRESENTED AS PERCENT IMPROVEMENT RELATIVE TO SCORES FOR CONVENTIONAL DISPLAY.

MEASURE	PERCENT IMPROVEMENT OVER CONVENTIONAL	
	RATE	COMMAND
Glideslope RMS error, averaged across 4 segments of the approach (Table 3)	22	48
Glideslope mean error, averaged across 5 distances from ramp (Figure 8 & Table 6)	74	81
Glideslope error standard deviation, averaged across 5 distances from the ramp (Figure 8 & Table 6)	10	41
Lineup error standard deviation, averaged across 5 distances from the ramp (Figure 9 & Table 6)	21	11
Mean Landing Performance Score (LPS) (Table 7)	4	11
Standard deviation of touchdown point (distance down deck) (Table 8)	3	23
Standard deviation of touchdown point (distance from centerline) (Table 8)	6	29
Mean descent rate at touchdown (Table 7)	0	9
Standard deviation of descent rate at touchdown (Table 8)	13	20

SECTION IV

DISCUSSION

GLIDESLOPE CONTROL

The COMMAND display was shown to be better than the CONVENTIONAL display with several measures of glideslope control. Approach performance with the COMMAND display was more stable and accurate within a trial as shown by RMS error scores throughout the approach, and more stable across trials as shown by standard deviations of glideslope error scores sampled at specific distances from the ramp. Two glideslope-related touchdown parameters: distance from the ramp, and descent rate, were also more stable across trials with the COMMAND display.

The results indicating more accurate and stable performance with the COMMAND display were not only statistically reliable, but appear substantial. The proportion of variance accounted for by the COMMAND/CONVENTIONAL comparison approximated 0.10 throughout the approach. Even more impressive from an operational standpoint is the fact that RMS error scores and standard deviations for the COMMAND display were 40% to 50% better than those for the CONVENTIONAL display. This improvement tended to be less substantial near the ramp and at touchdown, but even here the advantage shown with the COMMAND display appears large enough to affect boarding rates and safety.

It is likely that this reduction in the effectiveness of the COMMAND display near the carrier is related to the sensitivity of the arrows. As the experiment progressed it became evident that neither of the first-order displays provided a sufficiently precise indication of descent rate close to the ship. Sensitivity of the arrows was set at a level that during pretesting appeared to be optimum during the middle of the approach. As a consequence, during approximately the final 1000 ft. of the approach it was possible for a significant error to develop so gradually that the arrows were activated only very slightly or not at all. It is therefore plausible that the assistance from the arrows was reduced in close, and that the performance advantage shown in close with the COMMAND display was due in large measure to the pilot's improved ability to stabilize his approach further from the carrier. By increasing the arrows' sensitivity, or possibly by varying sensitivity as a function of range, it may be possible to increase further the effectiveness of the COMMAND display in close.

Performance with the RATE display tended to lie between performance with the CONVENTIONAL and COMMAND displays. The early approach data clearly showed the RATE display to be intermediate to the other two displays but the differences tended to shrink near touchdown. There was no detectable performance advantage with the RATE display in relation to the CONVENTIONAL display near and at touchdown on some of the measures, and the apparent performance advantage of the COMMAND display in relation to the RATE display was often not statistically reliable.

Nevertheless, although the RATE display was not always more effective than the CONVENTIONAL nor less effective than the COMMAND displays throughout the approach, it seems reasonable to conclude that it was of intermediate effectiveness.

The evidence from analyses of bias measures (mean error) was more ambiguous than the measures of stability. This is partially due to the fact that the operational significance of bias measures is more difficult to ascertain. For example, a low approach might be viewed more seriously than a high approach of equivalent error, but less seriously than a high approach of several times the error. The means of glideslope errors sampled at specific points from the ramp showed that early in the approach pilots tended to fly above the glideslope with the CONVENTIONAL display and close to it with the first-order displays. However, the critical sampling point at the ramp showed a negative bias for the three displays, with the bias of -1.62 feet for the COMMAND display being reliably larger than the bias of -0.12 feet for the CONVENTIONAL display.

Although low conditions at the ramp are potentially dangerous, this finding is not as detrimental to the COMMAND display as it may first appear. The negative bias at the ramp could have been due to the apparent tendency to drift low in the latter part of the approach because small errors were not clearly indicated by the arrows. Adjustment of the drive algorithm to provide higher sensitivity in close should correct this problem. Furthermore, it is important to recall that performance with the COMMAND display was more stable and inspection of glideslope errors at the ramp indicated that a dangerously low condition is more likely with the RATE and CONVENTIONAL displays.

Touchdown bias measures reflected the trends observed at the ramp. The means for landings with all displays were slightly short of the optimum touchdown point midway between the 2 and 3 wires. Descent rates are of particular interest at touchdown because a high descent rate can cause structural damage to the aircraft. The mean descent rate with the COMMAND display closely approximated the theoretical optimum of 8.58 ft. per sec., while mean descent rates for the CONVENTIONAL and RATE displays were reliably higher. In particular, extremely high descent rates were more prevalent with the CONVENTIONAL and RATE displays.

The need for better glideslope guidance has been well documented (Brictson, 1966, 1967; Perry, 1967; Durand et al, 1967; Winterberg, Brictson, & Wulfeck, 1964; Kennedy, Wulfeck, Prosin & Burger, 1974). The delay in implementing a better guidance system has been due to the lack of one that is both effective and economical. The data presented in this report show that the COMMAND display can improve glideslope performance significantly, and Kaul (1978) has suggested an approach for implementing this system in the fleet.

While there are abundant theories and data to indicate that first-order information would aid performance of a task such as glideslope tracking (Jensen 1979, McCormick 1970, Pew, 1966, Durand, 1967), the data obtained here have highlighted a finding that was not clearly implied by previous research. They have shown that a first-order system as represented in our COMMAND display can aid glideslope tracking to a greater extent than might have been expected. The fifty percent reduction in error generally found with the COMMAND display approximated that found by Kennedy, et al. (1974) with their predictor display. It might have been expected, on the basis of Jensen's (1979) comparison of prediction and quickening, that our COMMAND condition (a form of quickening) would have been somewhat less effective than the predictor displays listed by Kennedy, et al. It is encouraging that this relatively inexpensive system that would need only be installed on a few ships rather than several hundred aircraft (as in the case of the predictor display) can match the results obtained with the more complex system.

Vertical turbulence disrupted glideslope control as shown by RMS error and by the LPS. The effect was moderately strong close to the ramp where it accounted for 8.5% of the variance. The primary purpose of including environmental factors was to examine whether the FLOLS displays could affect performance under some conditions but not under others. Only two interactions (FLOLS display by time-of-day, and FLOLS display by turbulence) were statistically reliable. Neither of these accounted for more than 0.5% of the experimental variance and were judged to be of no operational significance.

LINEUP CONTROL

Concepts of workload would suggest that if the first-order displays assisted glideslope control they may also assist lineup control because the pilot could divert some of his attention, normally required for glideslope control, to the problem of lineup. Prior to the experiment there was some concern about an opposing point of view: namely, that the first-order displays would attract more than the share of attention normally paid to the FLOLS, and that lineup would suffer. The strong lineup enhancement shown by Kennedy, et al. (1974) was not considered relevant to this question because their predictor displays offered additional lineup guidance together with the additional glideslope guidance.

Neither view was strongly supported by the data, although there were some trends that favored the reduced workload hypothesis. There were no reliable differences for measures of RMS error or bias, but some tests of trial-to-trial stability showed reliable differences in favor of the first-order displays. The RATE/COMMAND comparisons generally showed performance with the RATE display to be less variable across trials, suggesting that pilots may have spent more time attending to the COMMAND display and therefore less to monitoring lineup. However, this effect is small (the difference between lineup standard deviations never exceeded 12' of arc) and could not be regarded as operationally significant.

Day approaches tended to be flown to the right of the centerline with the mean bias maintaining a constant value of 0.2° throughout the approach. Although a lineup bias of this magnitude (approximately 20 ft. at 6000 ft. from the ramp to 2.5 ft. near the ramp) is unlikely to be operationally significant, the effect was statistically reliable from 6000 to 1500 ft. from the ramp, and accounted for approximately 10% of the variance. The bias may have been due to pilots attempting to compensate for the left to right movement of the landing deck produced by the forward motion of the ship (effectively negated in this experiment with an appropriate environmental wind strength and heading) by aiming to the right of the landing deck. This is a commonly used strategy. Pilots may have headed directly towards the landing deck at night because there were fewer visible features outside of the landing deck that were appropriate for an aiming point. Whatever the cause it is interesting to note that biases of similar magnitude and direction have been observed with shipboard day and clear visibility night recoveries (Brictson, 1966).

The only other reliable environmental effect on lineup was the effect of time-of-day on touchdown variability. Lateral dispersion at touchdown was smaller for day than for night approaches, suggesting that, in spite of the bias to the right, day lineup performance was more stable.

ANGLE OF ATTACK CONTROL

Angle-of-Attack RMS was reliably influenced only by turbulence, which accounted for a substantial 50% of the variance for this measure. Most of this effect was probably due to the direct action of the random gusts on the AOA. The turbulence model that was used applied only vertical gusts, and some of the disturbance frequencies were too high to be tracked by the pilot. Thus the disturbance model caused the AOA to oscillate independently of the pilot's response, a fact that contributed heavily to the effect of turbulence on AOA RMS.

CONTROL ACTIVITY

FLOLS type had no effect on the measures of control activity that were examined. There was a tendency for lateral stick and rudder pedal activity to be higher with night than with day approaches. This presumably reflected some differences in strategy for controlling lineup. Elevator control and throttle activity were reliably higher for turbulent than for calm conditions throughout the approach. This probably reflected the increased difficulty of tracking the glideslope in the presence of the vertical gusts supplied by the turbulence model.

GENERAL COMMENTS

A first-order display similar to either of those tested in the experiment could be provided on a carrier by integrating a relatively inexpensive optical tracker with existing hardware. With similar reductions in glideslope error at the ship as were found in the VTRS with the COMMAND display, night bolter rates would be reduced substantially. Glideslope related accidents such as ramp strikes and hard landings could also be reduced considerably from the current rate. This system clearly has potential for improving efficiency at the ship and for saving aircraft and lives.

Aside from their operational significance first-order displays might help students learn to use a conventional FLOLS display more effectively. Lintern (1980) has shown that simulator training of light aircraft landings can be enhanced with the use of supplementary visual guidance cues. Weller (1979) has argued that guidance, predictor, or first-order displays might similarly teach appropriate glideslope-control techniques for carrier landings. The value of first-order displays similar to those tested here will be included in a comprehensive study of supplementary guidance for carrier landing training at the Naval Training Equipment Center.

Prior to or along with field evaluations of a prototype system, further simulation testing could establish the value of the COMMAND display under various conditions not tested in this experiment. Of particular interest is the possibility that aircraft with different handling characteristics would require slightly different command drive algorithms in order for the arrows to be of maximum benefit. Control response delays and aerodynamic stability of the aircraft could be easily manipulated in the simulator in order to explore this possibility. It would also be of interest to manipulate seastate in order to assess the display's effectiveness when the carrier is rolling, pitching and heaving. In addition, as previously discussed, an increase in the sensitivity of the arrows, particularly during the final 1000 ft. of the approach, would probably be helpful and should be examined. Finally, limitations in the resolution of the sensor used for tracking the aircraft might create a problem for first-order shipboard displays. If so, one solution might be to switch the arrows off until the aircraft is close enough to allow reasonable resolution of its position. The effect on glideslope performance of arrow activation at different ranges should therefore be examined. It is anticipated that these factors will be investigated in the near future.

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APPENDIX A

CONVENTIONAL FLOLS DISPLAY NOMENCLATURE

The FLOLS, the primary USN CV Visual Landing Aid (VLA) currently operational, provides instantaneous zero-order relative position information only. The position of the meatball relative to the datum bars is proportional to angular aircraft displacement from the projected FLOLS glideslope. These characteristics are simulated in the VTRS by determining the appropriate aircraft displacement angle, Θ_e, corresponding to known aircraft position updated each computing interval (refer to Figure 6 and Figure A1).

$$\Theta_e = \Theta_m - \Theta_L$$

where Θ_L = basic FLOLS projected glideslope angle

$$\Theta_m = \tan^{-1}\left[\frac{(h_a + h_L - y_t \tan \emptyset_L)}{r_a \text{COS } \delta_a \text{COS } B_a + 150 \text{ COS } \Theta_L}\right]$$

$$\delta_a = \text{SIN}^{-1}\left[h_a/r_a\right]$$

$$\beta_a = \text{SIN}^{-1}\left[y_t/r_a \text{ COS } \delta_a\right]$$

and $y_t = y_a + y_L$

As is evident from Figure A1, lateral flight path offset results in apparent meatball displacement due to roll-induced translation of the FLOLS beam-plane geometry.

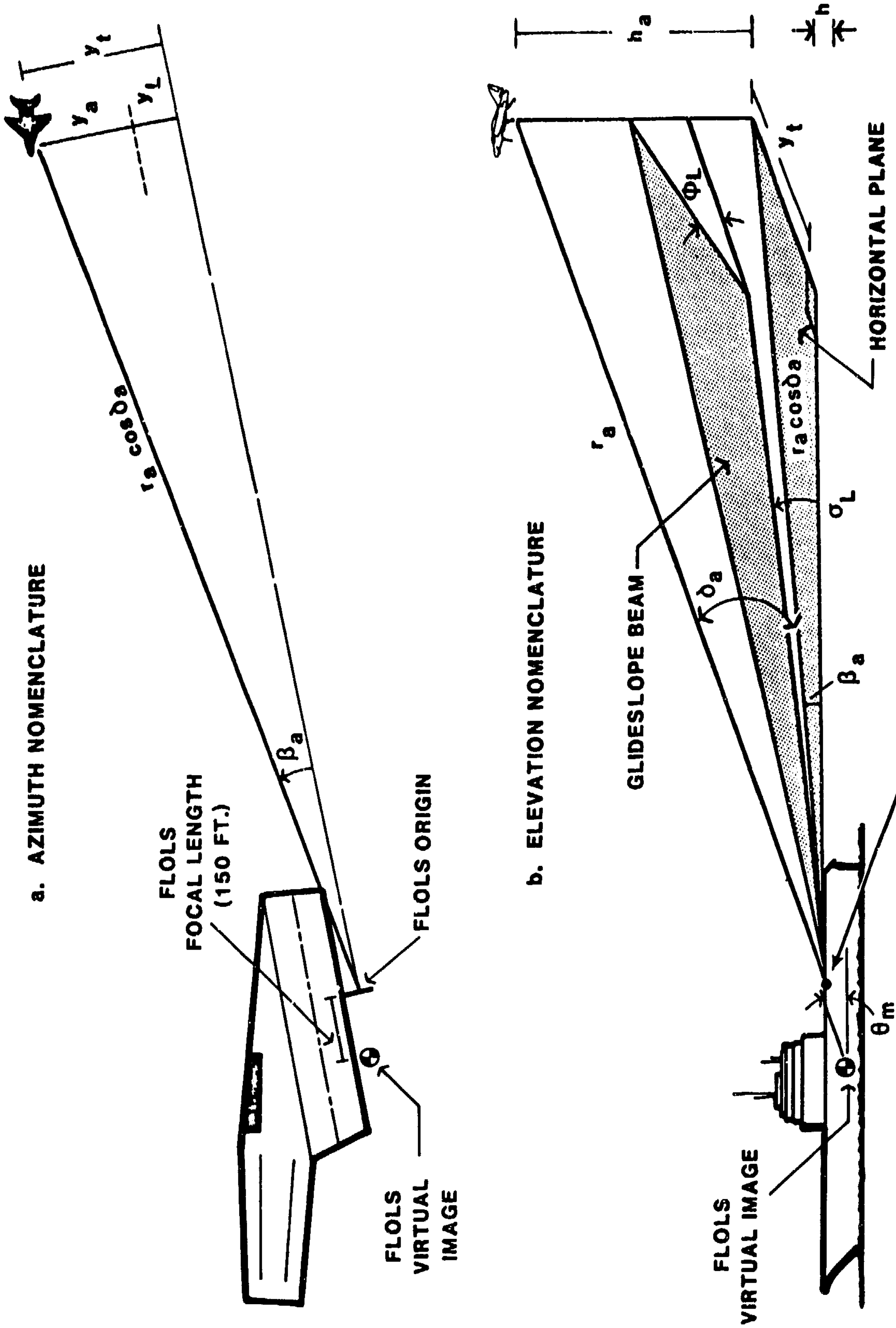

Figure A1. Simulated FLOLS Geometry

APPENDIX B

SUMMARY OF CONTROL ACTIVITY ANALYSES

TABLE B1. AVERAGE LATERAL STICK ACTIVITY (IN UNITS/SEC WHERE RANGE OF CONTROL DISPLACEMENT IS FROM -1 TO +1 UNITS): MEANS, STATISTICAL RELIABILITIES (*:p<.05, **:p<.01), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM RAMP (FT)	6000-1600		1600-400		400-0	
MEANS						
FLOLS TYPE (FL)						
Conventional (CONV)	.100		.147		.172	
Rate (RATE)	.107		.142		.164	
Command (COMM)	.111		.158		.199	
TIME OF DAY (Ti)						
Night	.117		.161		.186	
Day	.094		.137		.170	
TURBULENCE (Tu)						
Turbulent	.102		.146		.188	
Calm	.109		.152		.168	
RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2
FL	-	-	-	-	-	-
CONV vs RATE						
CONV vs COMM						
RATE vs COMM						
Ti	*	.012	*	.010	-	-
Tu	-	-	-	-	-	-
FL x Ti	-	-	-	-	-	-
FL x Tu	-	-	-	-	-	-
Ti x Tu	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-

TABLE B2. AVERAGE LONGITUDINAL STICK ACTIVITY (IN UNITS/SEC WHERE RANGE OF CONTROL DISPLACEMENT IS FROM -1 TO +1 UNITS): MEANS, STATISTICAL RELIABILITIES (*:p<.05, **:p<.01), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM RAMP (FT)	6000-1400		1400-400		400-0	
MEANS						
FLOLS TYPE (FL)						
Conventional (CONV)	.061		.094		.120	
Rate (RATE)	.062		.089		.127	
Command (COMM)	.068		.097		.130	
TIME OF DAY (Ti)						
Night	.064		.094		.124	
Day	.064		.092		.127	
TURBULENCE (Tu)						
Turbulent	.070		.105		.145	
Calm	.057		.081		.106	
RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2
FL	-	-	-	-	-	-
CONV vs RATE						
CONV vs COMM						
RATE vs COMM						
Ti	-	-	-	-	-	-
Tu	*	.020	*	.041	**	.062
FL x Ti	-	-	-	-	-	-
FL x Tu	-	-	-	-	-	-
Ti x Tu	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-

TABLE B3. AVERAGE RUDDER PEDAL ACTIVITY (IN UNITS/SEC WHERE RANGE OF PEDAL DISPLACEMENT IS FROM -1 TO +1 UNITS): MEANS, STATISTICAL RELIABILITIES (*:$p<.05$, **:$p<.01$), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM RAMP (FT)	6000-1600	1600-400	400-0
MEANS			
FLOLS TYPE (FL)			
Conventional (CONV)	.018	.027	.043
Rate (RATE)	.017	.025	.039
Command (COMM)	.017	.024	.036
TIME OF DAY (Ti)			
Night	.019	.029	.043
Day	.016	.021	.036
TURBULENCE (Tu)			
Turbulent	.018	.028	.044
Calm	.017	.023	.035

RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2
FL	-	-	-	-	-	-
CONV vs RATE						
CONV vs COMM						
RATE vs COMM						
Ti	-	-	*	.035	-	-
Tu	-	-	-	-	-	-
FL x Ti	-	-	-	-	-	-
FL x Tu	-	-	-	-	-	-
Ti x Tu	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-

TABLE B4. AVERAGE THROTTLE ACTIVITY (IN UNITS/SEC WHERE RANGE OF THROTTLE DISPLACEMENT IS FROM 0 to +1 UNITS): MEANS, STATISTICAL RELIABILITIES (*:$p<.05$, **:$p<.01$), AND VALUES OF ETA SQUARED (η^2).

DISTANCE FROM RAMP (FT)	6000-1600		1600-400		400-0	
MEANS						
FLOLS TYPE (FL)						
Conventional (CONV)	.016		.035		.089	
Rate (RATE)	.013		.032		.100	
Command (COMM)	.017		.036		.092	
TIME OF DAY (Ti)						
Night	.015		.034		.090	
Day	.016		.035		.098	
TURBULENCE (Tu)						
Turbulent	.018		.042		.111	
Calm	.013		.027		.077	
RELIABILITIES & η^2	p	η^2	p	η^2	p	η^2
FL	-	-	-	-	-	-
CONV vs RATE						
CONV vs COMM						
RATE vs COMM						
Ti	-	-	-	-	-	-
Tu	**	.039	**	.069	**	.050
FL x Ti	-	-	-	-	-	-
FL x Tu	*	.009	-	-	-	-
Ti x Tu	-	-	-	-	-	-
FL x Ti x Tu	-	-	-	-	-	-

APPENDIX C

EXCERPTS FROM QUESTIONNAIRES COMPLETED BY PILOTS AND LSO'S

I. Comments related to the general usefulness of the first-order displays, as compared to the CONVENTIONAL FLOLS.

"The (RATE and COMMAND) displays are a quantum improvement over previous systems and would greatly enhance carrier performance. For non-HUD aircraft this system would greatly reduce pilot workload."

"With (the arrows) the pilot has much greater control of the glideslope. He can see where the aircraft is going before the ball even moves...The system enables the pilot to make corrections with direct feedback as to what he just did--was it too much of a correction or too little? With the arrows he knows much sooner than the meatball can tell him. The pilot also will learn how to lead his corrections--an important technique students often have some trouble with."

"I found it totally unnecessary to look inside the cockpit for the VSI at any time while using the COMMAND or RATE displays. While using CONVENTIONAL I was inside the cockpit about 20% to check VSI."

"They both (RATE and COMMAND) work in the trainer; if they work like this in the fleet it will certainly take a lot of the 'pain' out of night carrier landings."

"In both COMMAND and RATE modes <u>all</u> passes, if graded from the start to the in-close position would have been "OK'S". This, in itself, would justify the adoption of this mod. Having all aircraft arrive in-close, stabilized with minor deviations, would be an LSO's dream."

"The fleet <u>cannot afford</u> to not get this system on their carriers. I would predict the carrier landing accidents would drastically reduce, if this system were in use."

"We need this mod. And we need it <u>now</u>. If we want to reduce pilot/LSO caused landing accidents immediately, put this on all carriers - <u>now</u>!"

II. Comments related to the relative effectiveness of the RATE versus the COMMAND system.

"Of the three systems, (COMMAND) is the best. It provides command information of what to do in order to keep the aircraft on the correct glideslope. In addition, provides the pilot the information for a correction if he is not on the correct glideslope. This effectively reduces the many "over controlled" calls that usually accompany a glideslope deviation."

"(With COMMAND) I would try to null out the arrows which I feel is preferable to the RATE technique of trying to guess at what correction was needed...By nulling the arrows the pilot knows that he will get back on the proper glideslope without over-controlling the aircraft."

"The COMMAND trajectory display I found to be a pleasant surprise. Initially I had felt that a computer generated optimum glideslope correction would be a distraction but I found it very easy to work with and an aid to making a smooth transition back to a centered ball. The real benefit of this type system (which was not really tested here) is the benefit to the pilot when he is well outside the normal glideslope and wants to make the best possible correction."

"The most exciting part of the COMMAND system is the starts to the in-close position were almost always right on. At least 95% of them. This is great! As an LSO if I see the pilot have a good start and maintain it half the battle is over."

"In general I liked the RATE mode better than the COMMAND mode. The pilot knows best how to put his particular aircraft on the glideslope with his techniques. The COMMAND mode is in effect telling the pilot what it thinks is the best method (rate of descent) to get back on glideslope."

"COMMAND mode not only illustrates the aircraft's position, but clues the pilot in his correction - both type and magnitude. In so doing, I would expect this mode to have a secondary beneficial effect of teaching some average to below average pilots proper and timely corrections while flying an approach. It would be expected that this would carry over when in the conventional mode."

"There is no doubt whatsoever that this system (COMMAND) would produce safer passes at the boat. Especially at night. The greatest impact would probably be noticed in excellent starts till in-close."

"This concept (COMMAND) is outstanding and a long time coming...It greatly reduced the workload of the approach from the start to in the middle and helped you smoothly transition to the tighter control required from the in-middle to in-close...A night landing would be more enjoyable if I had this system to look at."

LIST OF SYMBOLS

b	Location at which the command-function intercepts the vertical axis, ft/sec (Figure 7)
h_a	Aircraft altitude with respect to FLOLS origin, ft.
h_L	Height of FLOLS origin with respect to virtual image, 9.16 ft.
i	Indicates computation of given parameter at a discrete time instant or visual display frame
k_0	Augmented display vertical light bar scale factor, 0.63
k_1	Slope of the command-function, -0.15 sec^{-1}
l_a	Length of augmented display arrows, ft.
r_a	Slant range from FLOLS origin to aircraft, ft.
r_L	Slant range from FLOLS virtual image to aircraft, ft.
$\dot{s}_c$	Commanded displacement rate, ft/sec.
s	Aircraft displacement from glideslope, perpendicular to r_L, ft.
$\dot{s}$	Component of aircraft velocity perpendicular to r_L, ft/sec.
$\dot{s}_e$	Linear glideslope displacement rate error, ft/sec.
w	One-half of command-function deadband width, ft.
y_a	Lateral distance in ground plane from aircraft to angle-deck centerline, ft.
y_L	Lateral distance in ground plane from FLOLS roll axis to angle-deck centerline, 85 ft.
y_t	Lateral distance in ground plane from aircraft to FLOLS roll axis, ft.
β_a	Aircraft lateral displacement angle in ground plane measured from FLOLS origin, deg.
δ_a	Aircraft elevation angle with respect to FLOLS origin, deg.
Θ_e	Angular displacement of aircraft above (+) or below (-) nominal glideslope, deg.
Θ_L	FLOLS nominal projected glideslope angle, 3.5 deg.

Θ_m	FLOLS meatball elevation angle with respect to horizon, deg.
τ	VTRS computational interval time constant, .033 sec.
ϕ_L	FLOLS roll angle, deg. (CCW-positive as viewed by pilot)

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